**Defence Research and
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pour la défense Canada

Active Acoustics using Bellhop-DRDC

*Run time tests and suggested configurations for a
tracking exercise in shallow Scotian waters*

Dr. Diana McCammon
McCammon Acoustical Consulting

McCammon Acoustical Consulting
475 Baseline Road
Waterville, NS
B0P 1V0

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14. ABSTRACT

This research is designed to provide support for active sonar projects resulting from the bilateral agreement that has recently been signed with the US Navy to jointly investigate tactical oceanography technologies. In the context of the tracking exercise requirements, the model Bellhop-DRDC has been enhanced to produce active transmission loss and reverberation. Critical to the implementation of this model in the tracking exercise is the runtime. This report documents the parameters that affect runtime in Bellhop and recommends a configuration designed to provide the best result for the tracking exercise in terms of the accuracy/runtime trade-off. A Scotian shelf area was chosen as a representative exercise environment. Based on the timing and accuracy tests described in this report, it is recommended that for operation at 1000 Hz or higher in 260m water depth or less, the angle fan can be set to 30º (±15º) and a kill-after-bounce number of 7 can be safely employed to show less than 2dB error over all range and depth points in a 20km box. Using this configuration in Bellhop, a simulated test sequence was constructed to compute arrays of transmission loss and reverberation for 18 assets (one source, one towed array and 16 buoys) as a function of bearing angle, range (1/2km spacing out to 20km) and depth (51 points in 260m depth). This sequence was exercised for various numbers of lines of bearing and SSP points. These tests showed that the runtime needed for an initial calculation for all 18 assets ranged up to 12 minutes for 15 lines of bearing. The ping-by-ping update runtimes ranged up to 80 seconds for 15 lines of bearings and the 2 moving assets (one source and one towed array). These times were recorded using a 1.5GHz Pentium 4 processor.

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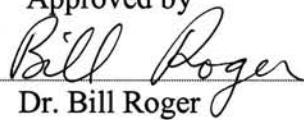
Dr. Bill Roger

Scientific Authority

Approved for release by

Kirk Foster

DRP Chair

Abstract

This research is designed to provide support for active sonar projects resulting from the bilateral agreement that has recently been signed with the US Navy to jointly investigate tactical oceanography technologies. In the context of the tracking exercise requirements, the model Bellhop-DRDC has been enhanced to produce active transmission loss and reverberation. Critical to the implementation of this model in the tracking exercise is the runtime. This report documents the parameters that affect runtime in Bellhop and recommends a configuration designed to provide the best result for the tracking exercise in terms of the accuracy/runtime trade-off.

A Scotian shelf area was chosen as a representative exercise environment. Based on the timing and accuracy tests described in this report, it is recommended that for operation at 1000 Hz or higher in 260m water depth or less, the angle fan can be set to 30º (±15º) and a kill-after-bounce number of 7 can be safely employed to show less than 2dB error over all range and depth points in a 20km box. Using this configuration in Bellhop, a simulated test sequence was constructed to compute arrays of transmission loss and reverberation for 18 assets (one source, one towed array and 16 buoys) as a function of bearing angle, range (1/2 km spacing out to 20km) and depth (51 points in 260m depth). This sequence was exercised for various numbers of lines of bearing and SSP points.

These tests showed that the runtime needed for an initial calculation for all 18 assets ranged up to 12 minutes for 15 lines of bearing. The ping-by-ping update runtimes ranged up to 80 seconds for 15 lines of bearings and the 2 moving assets (one source and one towed array). These times were recorded using a 1.5GHz Pentium 4 processor.

Résumé

Les présents travaux de recherche ont été élaborés afin d'apporter un appui aux projets sur les sonars actifs découlant de l'entente bilatérale conclue récemment avec les forces navales des É.-U. (US Navy) pour analyser conjointement les technologies d'océanographie tactique. Dans le contexte des exigences relatives à l'exercice de poursuite, le modèle Bellhop-RDDC a été amélioré pour générer la perte de transmission active et l'effet de réverbération. Le temps d'exécution est un élément critique à la mise en œuvre de ce modèle dans le cadre de l'exercice de poursuite. Le présent rapport porte sur les paramètres qui influent sur le temps d'exécution dans le modèle Bellhop et recommande une configuration visant l'obtention des meilleurs résultats possibles pour l'exercice de poursuite, en termes de compromis entre la précision et le temps d'exécution.

Une zone de la plate-forme néo-écossaise a été choisie comme environnement représentatif pour l'exercice. En tenant compte des essais sur le temps et la précision décrits dans le présent rapport, on recommande que, pour une fréquence de fonctionnement égale ou supérieure à 1000 Hz dans une profondeur égale ou inférieure à 260 m, l'angle de couverture soit réglé à 30º (±15º). On peut utiliser, avec une certitude raisonnable, une valeur de 7 rebondissements

avant annulation pour obtenir une erreur inférieure à 2 dB sur toute la portée et à tous les points de profondeur dans une zone de 20 km^3. En utilisant cette configuration dans le modèle Bellhop, on a généré une séquence simulée d'essai pour obtenir les diagrammes de perte de transmission et de réverbération pour 18 éléments (une source, un réseau remorqué et 16 bouées) en fonction de l'angle de relèvement, de la portée (variant entre ½ km et 20 km) et de la profondeur (51 points dans une profondeur de 260 m). Cette séquence a été essayée pour divers nombres de lignes de relèvement et de points SSP.

Les essais ont démontré que le temps d'exécution requis pour les calculs initiaux sur les 18 éléments atteint un maximum de 12 minutes pour 15 lignes de relèvement. Les temps d'exécution correspondant à la mise à jour impulsion par impulsion atteignent un maximum de 80 secondes pour 15 lignes de relèvement et deux éléments mobiles (une source et un réseau remorqué). Ces temps ont été enregistrés à l'aide d'un processeur Pentium 4 de 1,5 GHz.

Executive summary

Introduction

This research is designed to provide support for active sonar projects resulting from the bilateral agreement that has recently been signed with the US Navy to jointly investigate tactical oceanography technologies. In the context of the sea trial requirements, the model called Bellhop-DRDC has been enhanced to produce active transmission loss and reverberation. Critical to the implementation of this model for the trial is the time required to execute certain functions. This report documents the parameters that affect the run time and recommends a configuration designed to provide the best result in terms of the accuracy/runtime trade-off.

Results

A Scotian shelf area was chosen as a representative exercise environment. Based on the timing and accuracy tests described in this report, it is recommended that for operation at 1000 Hz or higher in 260m water depth or less, the angle fan can be set to 30º (±15º) and a kill-after-bounce number of 7 can be safely employed to show less than 2dB error over all range and depth points in a 20km box. Using this configuration in Bellhop, a simulated test sequence was constructed to compute arrays of transmission loss and reverberation for 18 assets (one source, one towed array and 16 buoys) as a function of bearing angle, range (1/2 km spacing out to 20km) and depth (51 points in 260m depth). This sequence was exercised for various numbers of lines of bearing and sound velocity profile points.

These tests showed that the runtime needed for an initial calculation for all 18 assets took up to 12 minutes for 15 lines of bearing. The subsequent ping-by-ping update runtimes ranged up to 80 seconds for 15 lines of bearings and the 2 moving assets (one source and one towed array). These times were recorded using a 1.5GHz Pentium 4 processor.

The test results indicate that the Bellhop program runs fast enough to provide the required acoustic predictions to the US Navy's Likelihood Ratio Tracker (LRT) in a timely fashion.

Significance

The time taken to predict oceanographic parameters can significantly impact the utility of tactical decision aids during maritime operations. This contract determined the time taken to predict important parameters that will be required by the US Navy's Likelihood Ratio Tracker, and subsequently to other decision aids and data fusion modules. It was determined that the Bellhop program will be fast enough for these clients.

Future Plans

It is intended to integrate further enhancements that increase execution speed without significantly impacting prediction accuracy. Some refinements are needed to provide greater accuracy in the prediction of reverberation following a sonar ping. Finally, the program must be able to handle beam patterns for the directional sensors.

Sommaire

Introduction

Les présents travaux de recherche ont été élaborés afin d'apporter un appui aux projets sur les sonars actifs découlant de l'entente bilatérale conclue récemment avec les forces navales des É.-U. (US Navy) pour analyser conjointement les technologies d'océanographie tactique. Dans le contexte des exigences relatives à l'essai en mer, le modèle Bellhop-RDDC a été amélioré pour générer la perte de transmission active et l'effet de réverbération. Le temps requis par l'exécution de certaines fonctions est un élément critique à la mise en œuvre de ce modèle dans le cadre de l'essai. Le présent rapport porte sur les paramètres qui influent sur le temps d'exécution dans le modèle Bellhop et recommande une configuration visant l'obtention des meilleurs résultats possibles, en termes de compromis entre la précision et le temps d'exécution.

Résultats

Une zone de la plate-forme néo-écossaise a été choisie comme environnement représentatif pour l'exercice. En tenant compte des essais sur le temps et la précision décrits dans le présent rapport, on recommande que, pour une fréquence de fonctionnement égale ou supérieure à 1000 Hz dans une profondeur égale ou inférieure à 260 m, l'angle de couverture soit réglé à 30º (±15º). On peut utiliser, avec une certitude raisonnable, une valeur de 7 rebondissements avant annulation pour obtenir une erreur inférieure à 2 dB sur toute la portée et à tous les points de profondeur dans une zone de 20 km^3. En utilisant cette configuration dans le modèle Bellhop, on a généré une séquence simulée d'essai pour obtenir les diagrammes de perte de transmission et de réverbération pour 18 éléments (une source, un réseau remorqué et 16 bouées) en fonction de l'angle de relèvement, de la portée (variant entre ½ km et 20 km) et de la profondeur (51 points dans une profondeur de 260 m). Cette séquence a été essayée pour divers nombres de lignes de relèvement et de points de profil de célérité du son.

Les essais ont démontré que le temps d'exécution requis pour les calculs initiaux sur les 18 éléments atteint un maximum de 12 minutes pour 15 lignes de relèvement. Les temps d'exécution subséquents correspondant à la mise à jour impulsion par impulsion atteignent un maximum de 80 secondes pour 15 lignes de relèvement et deux éléments mobiles (une source et un réseau remorqué). Ces temps ont été enregistrés à l'aide d'un processeur Pentium 4 de 1,5 GHz.

Les résultats de l'essai indiquent que le programme Bellhop s'exécute de façon suffisamment rapide pour fournir, dans un court délai, au calculateur du rapport des vraisemblances (LRT pour *Likelihood Ratio Tracker*) de l'US Navy les prédictions acoustiques requises.

Portée

Le temps nécessaire pour prédire les paramètres océanographiques peut avoir un effet significatif sur l'utilité des aides à la prise de décisions au niveau tactique lors d'opérations maritimes. Les travaux effectués dans le cadre du présent contrat ont permis de déterminer le temps nécessaire pour prédire des paramètres importants qui seront requis par le LRT de l'US Navy et, par la suite, par d'autres aides à la prise de décisions et modules de fusion de

données. On a déterminé que le programme Bellhop sera suffisamment rapide pour ces clients.

Recherches futures

On a l'intention d'intégrer d'autres améliorations qui augmentent la vitesse d'exécution, mais n'ont pas d'effet majeur sur la précision des prédictions. En outre, certaines améliorations sont encore nécessaires pour obtenir une plus grande précision quant à la prédiction de la réverbération suite à une impulsion de sonar. Finalement, le programme doit être capable de traiter les diagrammes de faisceau dans le cas des capteurs directionnels.

Dr. D. McCammon. 2005. *Active Acoustics using Bellhop-DRDC: Run time tests and suggested configurations for a tracking exercise in shallow Scotian waters*, DRDC Atlantic CR 2005-087. Defence R&D Canada – Atlantic.

Table of contents

List of figures

List of tables

1.   Introduction

This research is required to provide support for active sonar projects. A bilateral agreement has recently been signed with the US Navy to jointly investigate tactical oceanography technologies in the context of Networked Underwater Warfare. Discussions on the direction of the research have highlighted the immediate and urgent need to enhance the capabilities of the Bellhop acoustic prediction model. Currently, this program is limited to predicting the response at an acoustic sensor from a signal generated by a noisy vessel in the vicinity. The focus of the bilateral research will be active acoustics, where an underwater projector emits a ping that reflects off nearby surfaces and is subsequently detected by the sensor. Although the Bellhop model contains the underlying elements necessary to predict active transmissions, these have not been utilized to provide the actual output. There is thus a requirement to enhance the capability of the Bellhop model to generate predictions of reverberation from active transmissions, and the expected signal excess in an active environment.

The tasks under this requirement are:
1. Roughly estimate the time required to generate a look-up table of active signal excess over a grid of source-sensor positions.
2. Generate the capability for Bellhop to predict signal excess in an active environment by enhancing the model to estimate the expected reverberation for the bistatic situation.

For active signal excess, the configuration of Bellhop is a subroutine called Bellhop-DRDC_SE which produces the arrival tables called SALT (Sound Angle, Level, and Time) tables for acoustic field points in range and depth as well as points at the surface and bottom for reverberation computations. These tables are stored and accessed in the module dataMod.f90. The CPU time quoted in this report is just the runtime of the subroutine Bellhop-DRDC_SE, to compute the SALT tables, and the array manipulation to assemble reverberation. There is no I/O included in this timing because all input and output variables are passed through the dataMod module.

2. Task 1 - Runtime

To configure the Bellhop-DRDC_SE subroutine to run as fast as possible, several questions need to be studied. First, what are the parameters that affect runtime and how large is their effect. Second, which of these parameters affect the accuracy of the result and what is the trade-off.

2.1 All parameters that affect runtime

In the Bellhop-DRDC_SE model, the number of rays being traced, the range to which each ray is traced, and the step size along the way determines the CPU runtime. The ray theory used by Bellhop is the Gaussian Ray Bundle (GRAB) method. In this method it is not necessary to find eigenrays, therefore the number of receiver depths and number of range sample points have only a very small influence on the run time. Range dependent changes in the bathymetry, bottom loss or sound speed profile have essentially no effect on the run time.

The number of rays being traced is a function of the angle fan specified by the user, the frequency and maximum range of the trace. The relation used in Bellhop-DRDC_SE for the suggested optimum number of rays is:

$$N = 2 + \theta \sqrt{\frac{6FR_{max}}{1500}}$$

where θ is the angle fan in radians, (for example, a 90º fan traces rays from -45º to +45º)
F is the frequency in Hertz,
R_{max} is the maximum range of the trace in meters.

The step size is chosen to be the smaller value of 10 wavelengths or $1/20^{th}$ of the water depth. Other factors that affect the runtime include the number of sound speed profile (SSP) points, an internal setting called the amplitude decay cutoff, and the number of bottom bounces permitted (called the kill-by-bounce number) which is a user setting.

In summary, the primary factors that affect runtime are: angle fan, frequency, maximum range, water depth (if smaller than 10 λ), number of SSP points, amplitude decay cutoff, and the kill-after-bounce cutoff.

2.2 Runtime parameters that also affect accuracy

Those parameters identified above that will affect the accuracy of the predicted acoustic field are the angle fan, the number of SSP points, the amplitude decay cutoff and the bottom bounce cutoff.

2.3 Timing/accuracy test setup - Scotia environment

To determine estimates of the runtime required for the creation of SALT tables, a typical environment is defined from the Scotian Shelf area consisting of a flat bottom at 260m and a sound speed profile that is typical for this area as shown in Figure 1. This environment was chosen to approximate the expected bilateral exercise environment. The lowest bottom loss

(MGS=1) is chosen and plotted in the figure for three of the frequencies in this test, 500 Hz, 750 Hz and 1000 Hz.
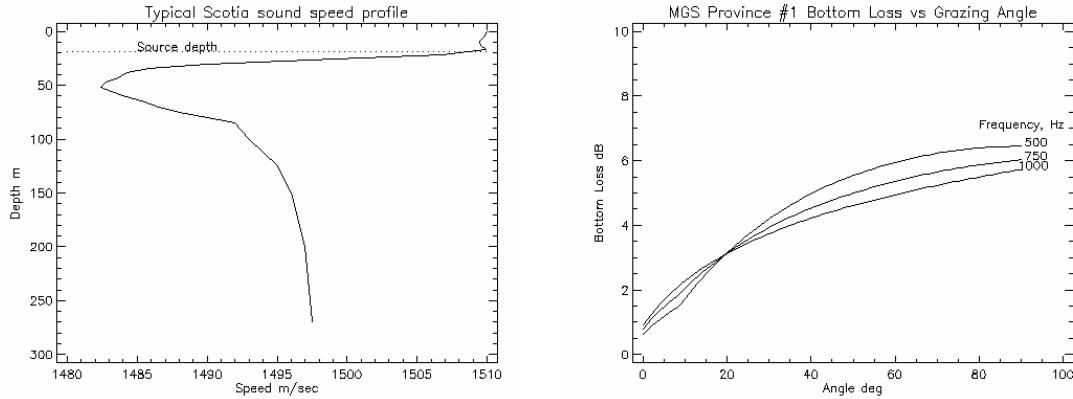
Figure 1. A 25 point sound speed profile and bottom loss for the frequency span of the tests.

The source is assumed to be at 18.3 m (60ft). Three rays are traced in Figure 2 (-2.5 °, -0.5 °, and +3.5 °) to show that none of the sound is being trapped in the small sound speed duct, and all rays are going to strike the bottom. Because of this intense bottom interaction, MGS 1 was chosen to extend the runtime as long as possible. (The tracing algorithm will terminate each ray after the running amplitude falls below the internal amplitude cutoff. This would cause high-loss bottoms to have faster runtimes than low-loss bottoms.). An example of an incoherent transmission loss field for this environment is shown on the left of Figure 2. It shows the sound fills the water column and decays more-or-less uniformly with range.

The timing tests for this environment are being conducted with the parameters and range of values listed in Table 1. The entries 1 through 4 affect the accuracy of the solution, so these will be tested first, using various values of frequency and range.

Table 1. Parameters and range of values tested

1	Internal amplitude cutoff	0.0001, 0.005, 0.01, 0.05, 0.1
2	Angle fan, degrees	120 (±60°), 90 (±45°), 60 (±30°), 40 (±20°), 30 (±15°), 20 (±10°)
3	Kill-after-bounce number	6, 7, 8, 9, 15
4	Number of SSP points	5, 10, 15, 20, 25
5	Max range, km	10, 15, 20, 25, 30
6	Frequency, Hz	500, 750, 1000, 1250, 1500
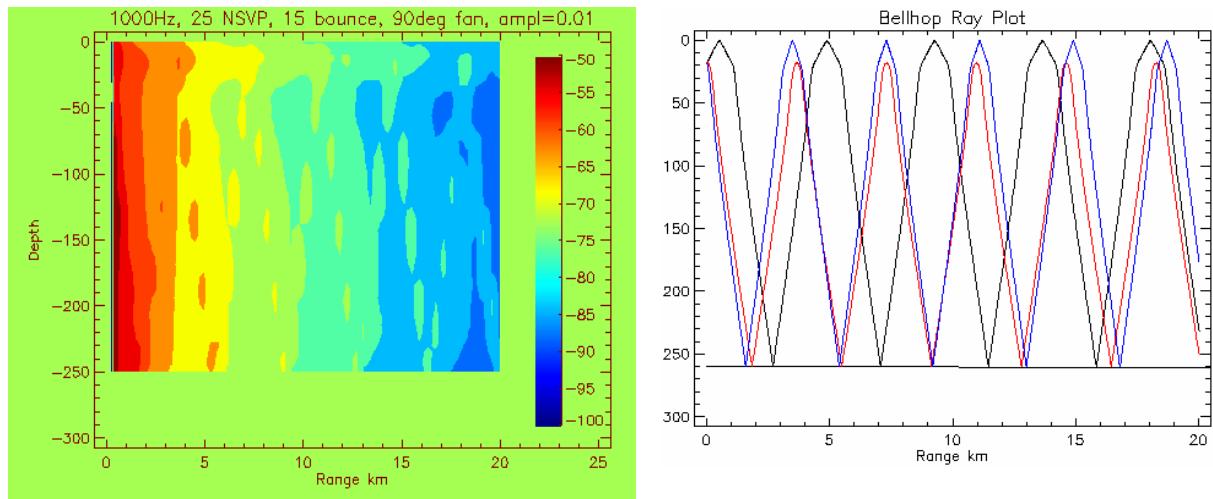
Figure 2. On the right, three rays are traced from –2.5º, -0.5º, and +3.5º from a source at 18.3m. On the left, an incoherent acoustic field is plotted for 1000 Hz, 90º angle fan.

2.4   Accuracy tests

The accuracy of a prediction will be illustrated by comparison between two full-field incoherent transmission loss plots. For this environment, it is appropriate to compare the incoherent transmission losses because, with so many bottom bounce interactions, the coherence among rays would be essentially destroyed, making the 'coherent' transmission loss output a fairly meaningless quantity.

2.4.1   Internal amplitude cut-off

In Table 1, the first entry is the internal amplitude cutoff. This value is not presently user modifiable. It is used to test the running amplitude in the ray-tracing loop for each ray's step. It terminates the ray when the running amplitude falls below this cutoff value. The value that was found in the original web-down loaded version of Bellhop was 0.005. Trial transmission loss fields were constructed using this parameter as a variable from 0.0001 to 0.1, and it was found that there was absolutely no loss of accuracy (results were identical) for cutoffs as large as 0.01. In this Scotia environment dominated by bottom bounce, the kill-after-bounce parameter will serve the same purpose as this internal amplitude cutoff, and since the kill-after-bounce number is a user input, it is reasonable to drop the testing of the amplitude cutoff. Therefore, for the remainder of the tests, the internal amplitude cutoff will be fixed at 0.01.

2.4.2 Angle fan

In Table 1, the second entry is the angle fan. This parameter defines the range of grazing angles to be traced from the source and is directly proportional to the optimum number of rays, as shown in the equation in section 1.1. The default value for this angle fan is currently 90º (±45º), which was the value found in the original web-down loaded version of Bellhop, however the user has the ability to specify any values in the input file. The following figures illustrate the accuracy and runtime trade-off that this selection will create. These tests were all conducted at 1000 Hz, 20 km, with 25 points in the SVP and a kill-after-bounce value of 15.

120º vs 90º angle fan

We consider the angle fan of 120 degrees (±60º) to be the highest fidelity calculation for this test. A transmission loss run using this angle fan takes 12.3 seconds and calculates 594 rays. The errors introduced by limiting the angle fan to 90º (±45º) with 446 rays are shown in Figure 3. All the errors occur at very close range around the source depth. The mean error is 0.066 dB. Excluding the short range where r<2km, there is no error.
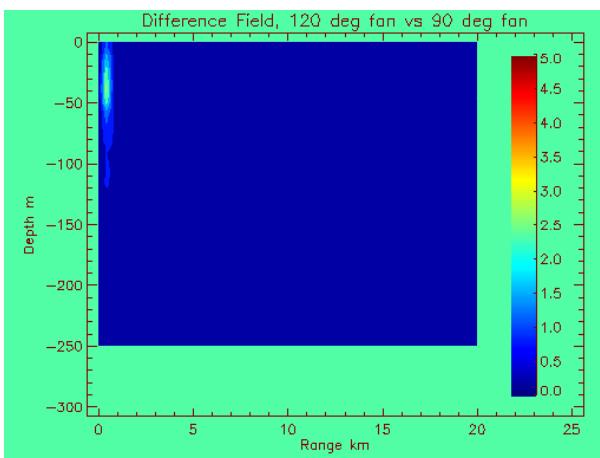
Figure 3. Comparison of the difference in dB between the full field transmission loss predictions using a 120º angle fan and a 90º angle fan.

120º vs 60º angle fan

The differences between the 120º and the 60º angle fan (±30º with 298 rays) are shown in Figure 4. Here, the differences at close range are considerably larger, nearly 5dB in some places, but these differences are localized at very close range around the source depth and at the bottom. This is to be expected since we are limiting the high angles. Now however, we are also seeing some differences beyond 15km of about 1-1.5 dB. The mean difference including the short range is 0.239 dB. The mean error excluding the short range r<2km is 0.164 dB.

120º vs 40º angle fan

The differences between these angle fans are shown in Figure 5. The 40º fan covers ±20º with 199 rays. The overall mean error is 1.255 dB, however if the short ranges less than 2km are excluded, the error falls to 0.31 dB.

The differences between these angle fans are shown in Figure 6. The 30º fan covers ±15º with 150 rays. The overall mean error is 1.879 dB, however if the short ranges less than 2 km are excluded, the error falls to 0.43 dB. Note that the short range error is creeping farther outward in range, but the long range errors have not changed.
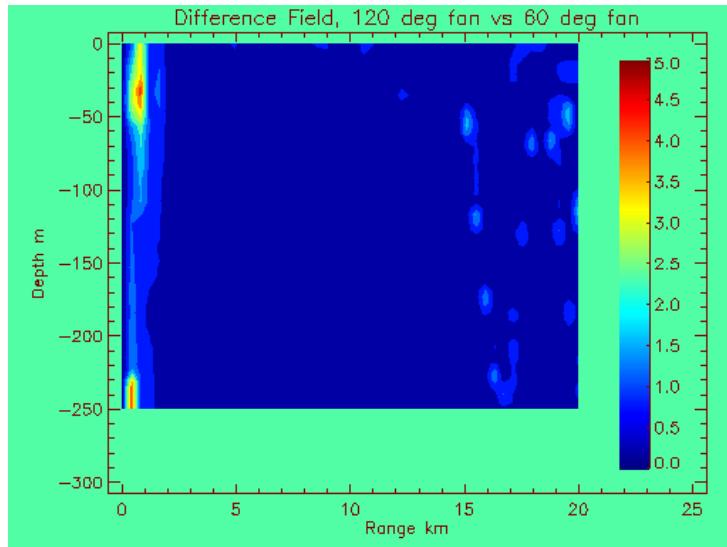
Figure 4. Comparison of the difference in dB between the full field transmission loss predictions using a 120º angle fan and a 60º angle fan.
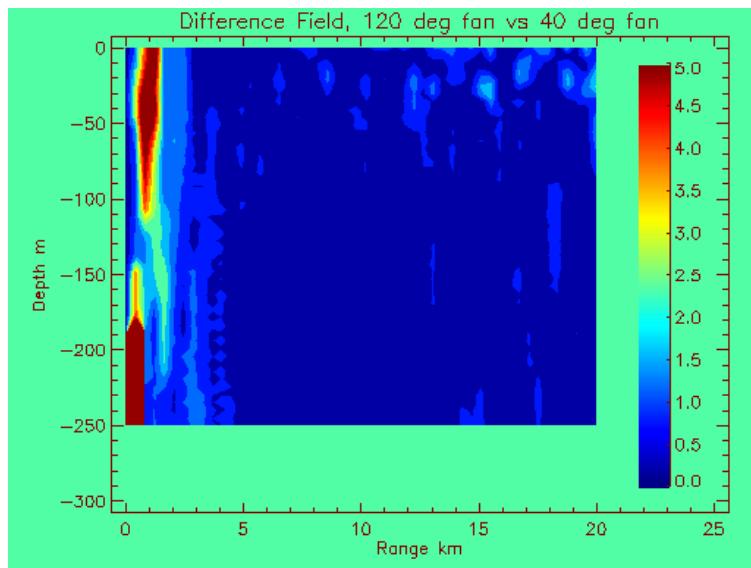
Figure 5. Comparison of the difference in dB between the full field transmission loss predictions using a 120º angle fan and a 40º angle fan.
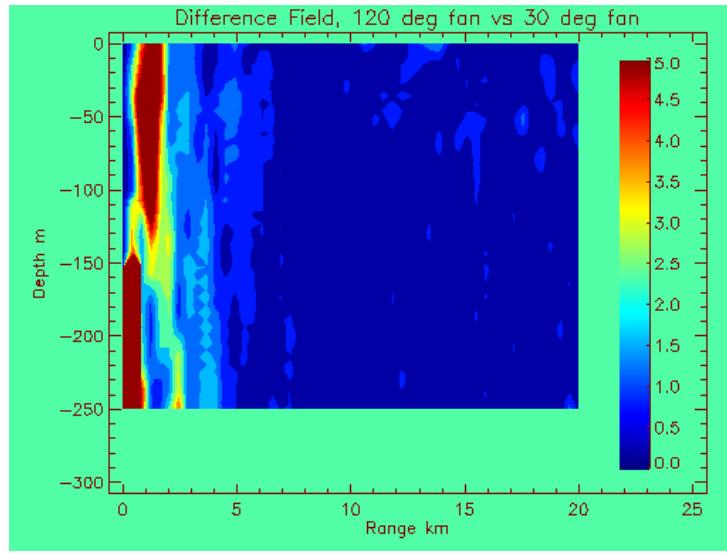
Figure 6, Comparison of the difference in dB between the full field transmission loss predictions using a 120º angle fan and a 30º angle fan.
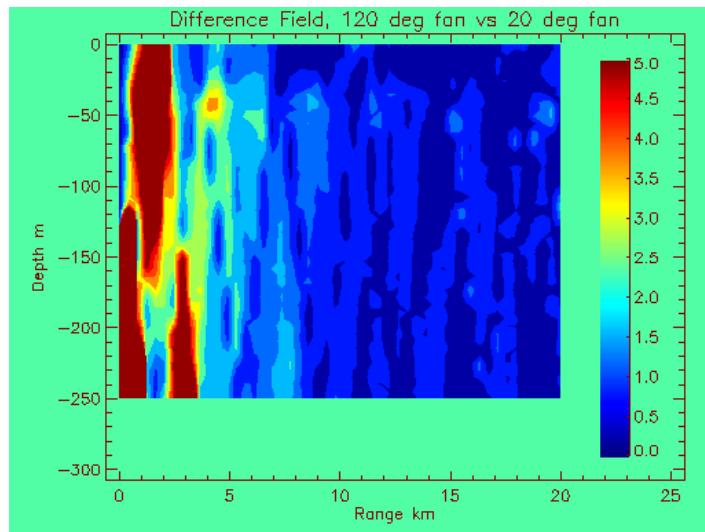

Figure 7. Comparison of the difference in dB between the full field transmission loss predictions using a 120º angle fan and a 20º angle fan.

120º vs 20º angle fan

The differences between these angle fans are shown in Figure 7. The 20º fan covers ±10º with 100 rays. The overall mean error is 3.233 dB and the errors beyond 2 km are 1.066 dB.

2.4.2.1 Angle fan summary comparisons

A comparison of the CPU time and the errors vs the angle fan value is shown in Figure 8. These graphs show that the overall errors rise rather dramatically for fans smaller than 60º. However, the errors at 30º are still quite acceptable, and the decrease in CPU time from 60 to 30 is about 4 sec, which is substantial. I can comfortably recommend the 30º fan.
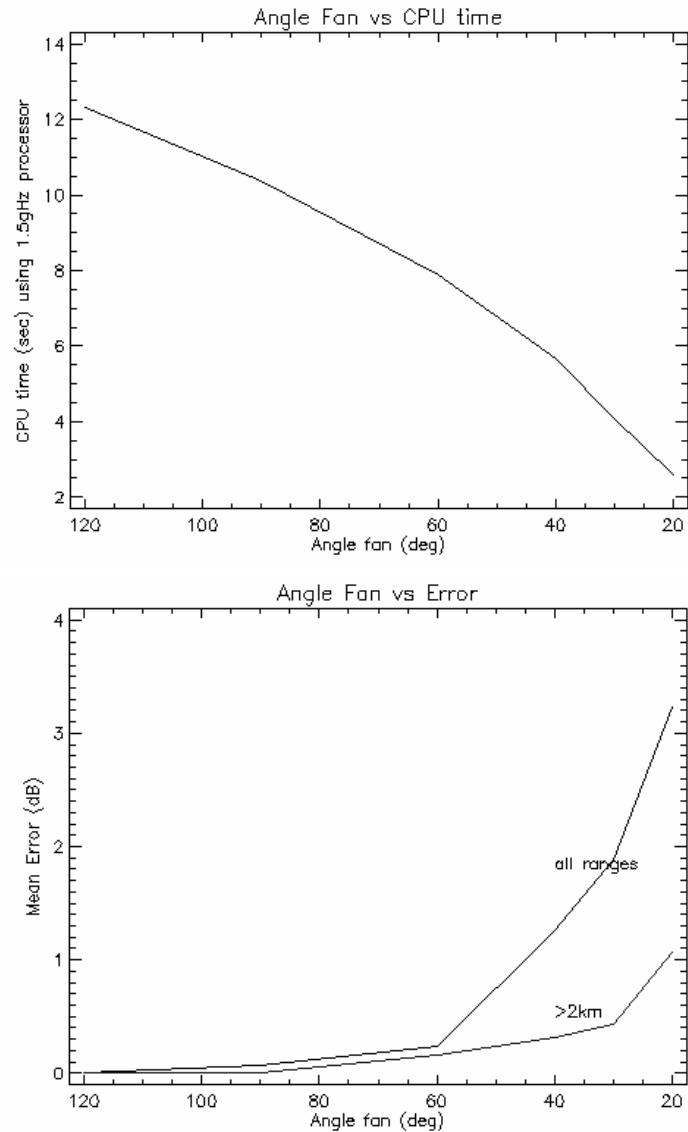
Figure 8. Graphs of angle fan vs CPU time and error.

2.4.3 Kill-after-bounce parameter

The kill-after-bounce parameter allows the user to limit the number of bottom bounces that each ray will have. The following tests exercise this parameter using a 60º angle fan at 500 Hz with the 25 point sound speed profile and a maximum range of 30km. Figure 9 displays the differences between the result that allowed 15 bounces vs 9 and 8 bounces. The major differences occur at the longest range, as might be expected. It appears that the choice of 9 bounces at this range and frequency would be safe. This test was rerun using a 40º angle fan and the resulting error maps looked almost identical, although the run time was faster.

Another test was run using a 60º angle fan at 1000 Hz with a maximum range of 20 km. In this case, because of the shorter range and higher frequency, the error curve is smaller, and the accuracy would be acceptable by limiting the bounces to as low as 7.
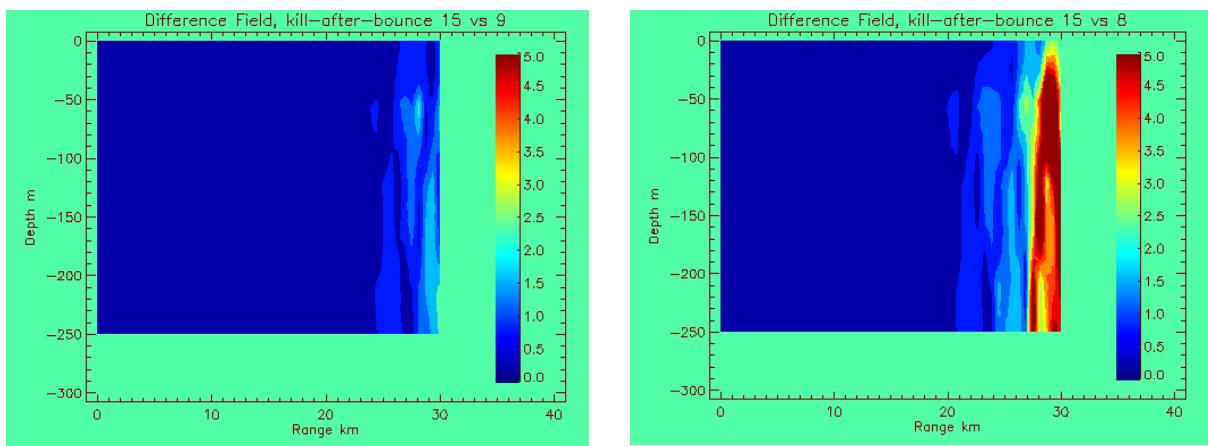
Figure 9. TL field differences for the Kill-after-bounce 15 vs 9 (left) and 8 (right) for 500 Hz, 30 km using a 60º angle fan.

2.4.3.1   *Kill-after-bounce summary comparisons*

The graphs in Figure 10 show time and error in four kill-after-bounce tests: 500 Hz to 30km with a 60º angle fan; 500 Hz to 30km with a 30º fan; 1000Hz to 20 km with a 60º fan; and 1000Hz to 20km with a 30º angle fan. In the upper graph, the time is seen to be approximately the same for either frequency & range choice in the same angle fan. However in the lower graph, the errors are much larger at the lower frequency, longer range test. This is because there is less loss from each bounce and more bounces are needed to describe the field at the longer range. This error curve indicates that the safest kill-after-bounce choice for all frequencies, ranges, and angle fan choices would be 9 bounces, however at 1000Hz and above, 7 bounces gives quite an acceptable result having an error less than 0.144dB.
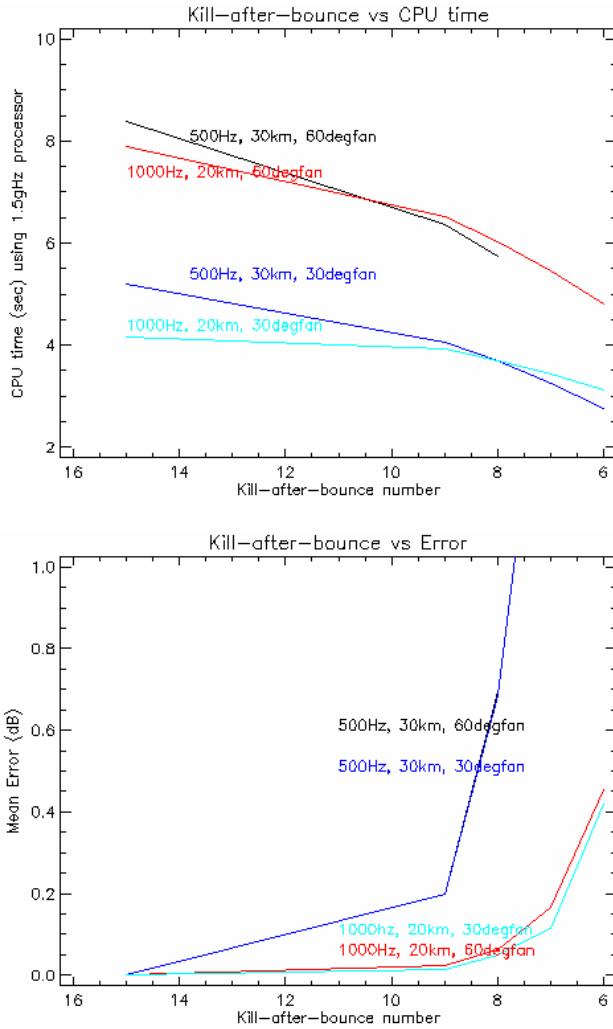
Figure 10. Graphs of Kill-after-bounce number vs CPU time and error at different angle fans, frequencies and range combinations.

2.4.4 Number of sound speed profile points

Ray traces work by stepping through the sound speed profile as they trace the trajectory of a ray. The input profile is linearly interpolated between points in Bellhop-DRDC_SE as required for each step. In this test, we vary the input number of sound speed profile (SSP) points by sub-sampling a profile. The base profile will be the 25-point profile shown in **Figure 1**. This will be sub-sampled down to 20, 15, and 10 points as shown in Figure 11. In these tests, the longest range of 30 km was chosen, since the errors we expect can occur anywhere within the water column. An angle fan of 60º and a kill-after-bounce number of 9 is selected for these tests. The frequencies examined will be 500 Hz, 1000 Hz and 1500 Hz. An example of the difference fields generated by these tests is shown in Figure 12 for the 1500 Hz test cases, where you can see the errors distributed more-or-less equally over the entire

water column, except at the lowest sampling rate where the errors increase dramatically with range.
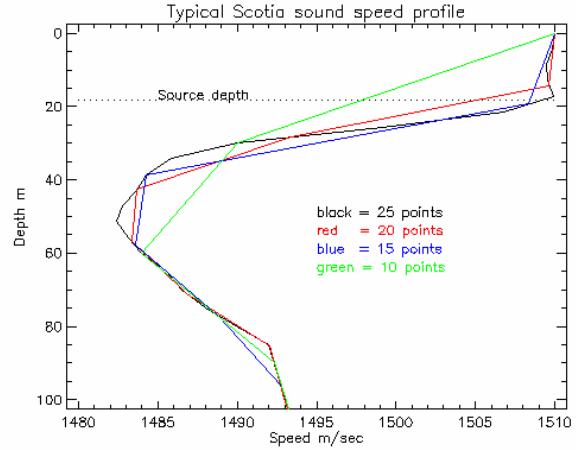
Figure 11. Upper water column graph of 4 sub-sampled sound speed profiles.
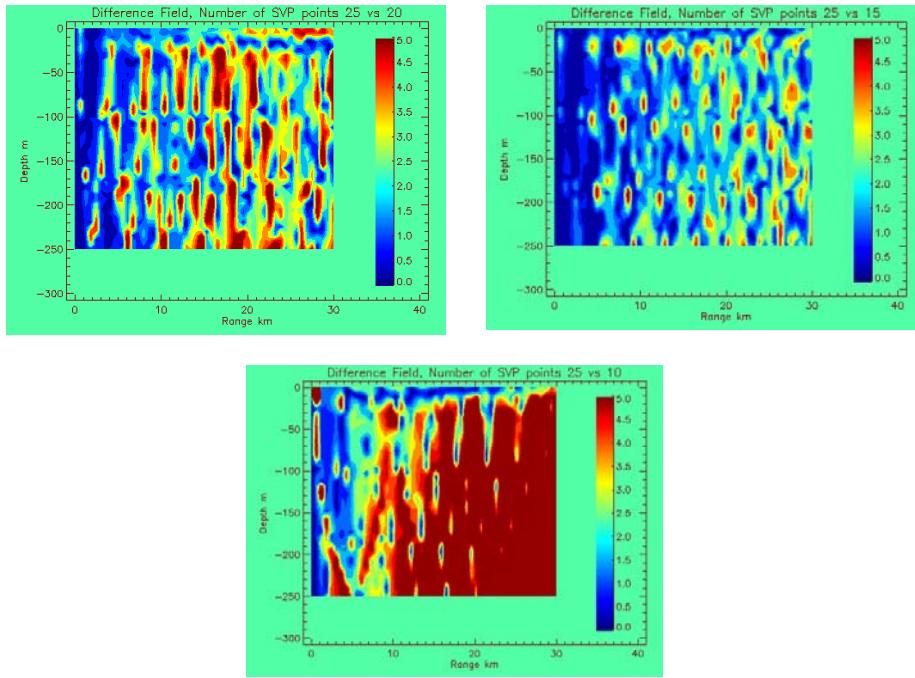
Figure 12. TL differences at 1500 Hz for changes in sound speed profile points. Top left = 25 vs 20, top right = 25 vs 15, bottom = 25 vs 10.

2.4.4.1   *SSP points summary comparisons*

The CPU runtime and errors obtained from these sound speed profile tests are graphed in Figure 13 for the three frequencies tested.

Number of Sound Speed Points vs CPU time

Number of Sound Speed Points vs Error
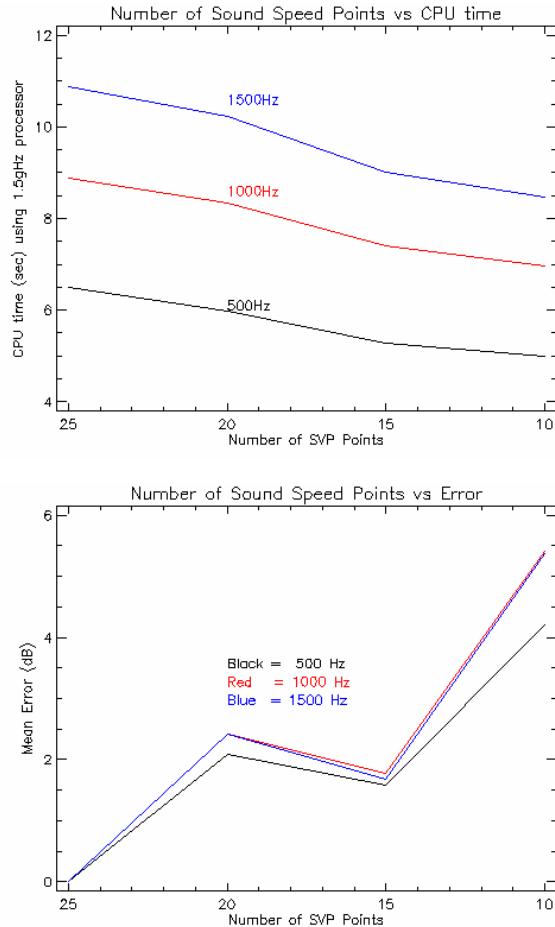
Figure 13. Graph of CPU time and error for changes in the number of sound speed profile points used in the trace.

First we note that all the trends are the same across the frequency band. The 500 Hz case runs almost twice as fast as the 1500 Hz case. The errors shown in the bottom graph illustrate an important phenomenon. The errors are nearly identical at all frequencies and there is actually a dip in all the curves at the 15-point profile. That is, the 15-point profile was a more faithful representation of the 25-point profile than was the higher sampled 20-point profile. This is a result of my sampling process, which is an automated linear interpolator. No attempt was made to select "intelligently" by carefully sampling around the inflection points at 19m and from 35m to 60m where the profile changes direction sharply. The 15-point profile must have accidentally landed on the critical inflection points more closely than the 20-point or 10-point profiles.

This serves as a warning that there will be no easy way to determine just what the best sound speed profile sample rate is. Certainly, keeping all available points may be over-kill. One

should be able to remove redundant points in iso-velocity and linear segments with little loss in accuracy and potentially a good savings in run time. For example, if we carefully select the SVP values from the 25-point profile to produce the 10-point profile shown in Figure 14, then the difference field error is greatly reduced. Compare the right hand side of Figure 14 to the bottom difference field in Figure 12. The error has been reduced dramatically by a factor of 10 from 5.38 to 0.510 dB while the times are commensurate at 8.4 sec and 8.1 sec. Thus, with this carefully selected profile, we can retain the accuracy to within ½ dB while reducing the runtime over the 25-point profile by 2.5 seconds.

Clearly, it pays to carefully select the sound speed profile points. If time permits on the bilateral exercise site, it would be useful to make a few test runs with sampled profiles to determine the best choices.
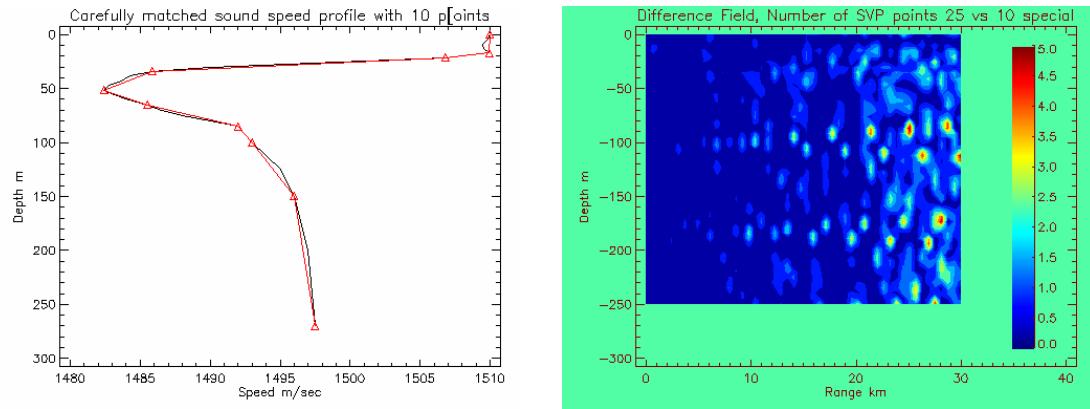
Figure 14. Left: 10-point speed profile carefully selected to match the 25-point profile at inflection points. Right: TL Difference field at 1500 Hz using the carefully selected profile. Mean error has been reduced from 5.38dB using the automated 10-point profile (see Figure 12) to 0.51 dB using the carefully selected 10-point profile.

2.5   Other timing factors not affecting accuracy

The optimum-number-of-rays calculation shown in section 1.1 was proportional to the square root of the frequency and maximum range. These factors will therefore influence the run time although they will not have any impact on the accuracy.

2.5.1   Maximum range and frequency

The tests for timing have been run for combinations of the maximum range and the frequency assuming the accuracy questions are best answered by using an internal amplitude cut-off of 0.01, an angle fan of 60º, 9 bottom bounces, and a careful selection of profile points. Second sets of timing runs assume slightly less accuracy by using a 30º angle fan, and 7 bottom bounces. The following graphs, Figure 15(60º angle fan, 9 bounce) and Figure 16(30ºangle fan, 7 bounce), display these timing tests. From these figures, we see that the trends are identical between the two angle fans, with the larger fan/bounce combination using about twice as much run time.
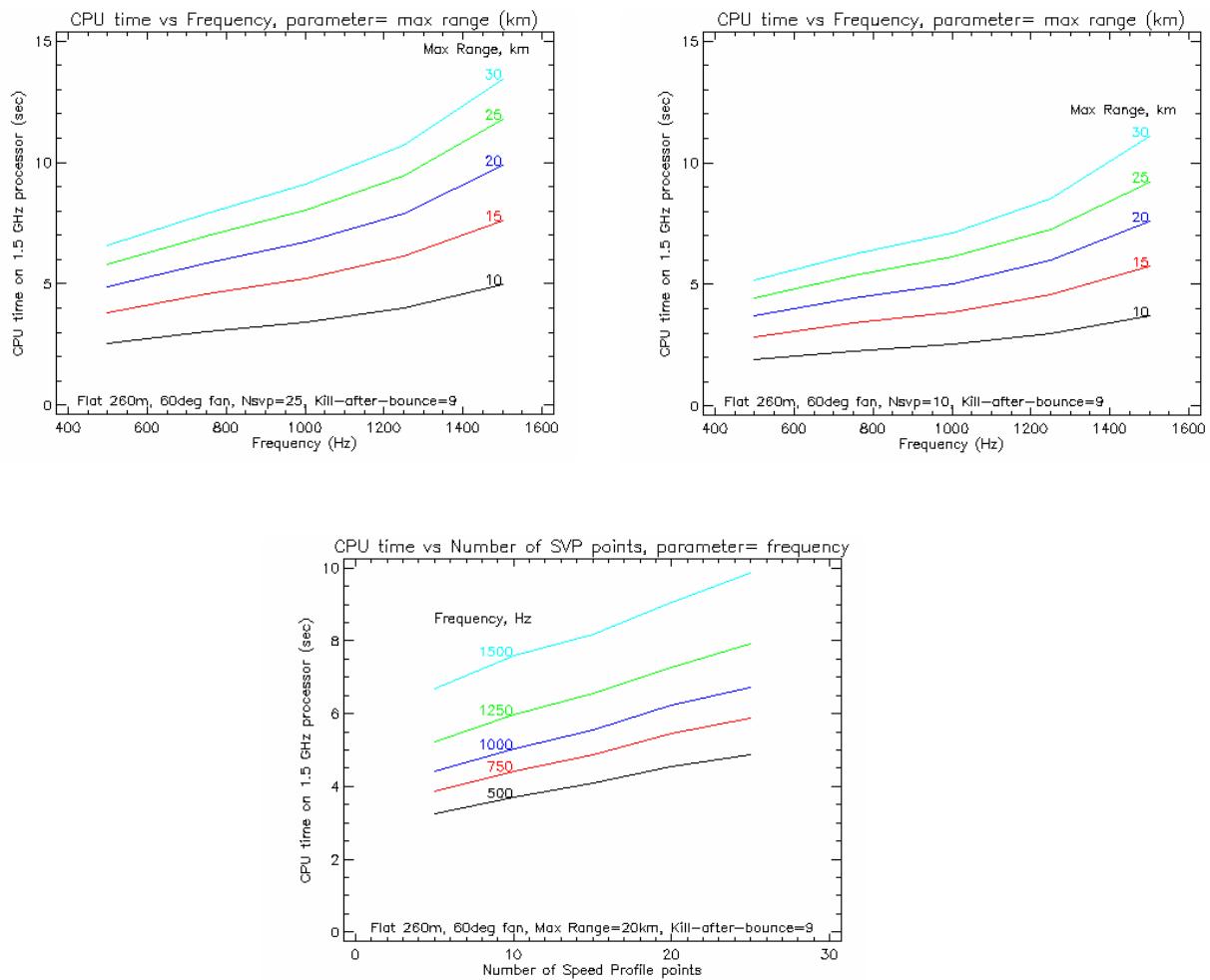
Figure 15. CPU time vs frequency and number of profile points for a 60ºangle fan allowing 9 bounces. Upper left uses a 25 point SSP, upper right uses a 10 point SSP. Lower graph uses a max range of 20km.
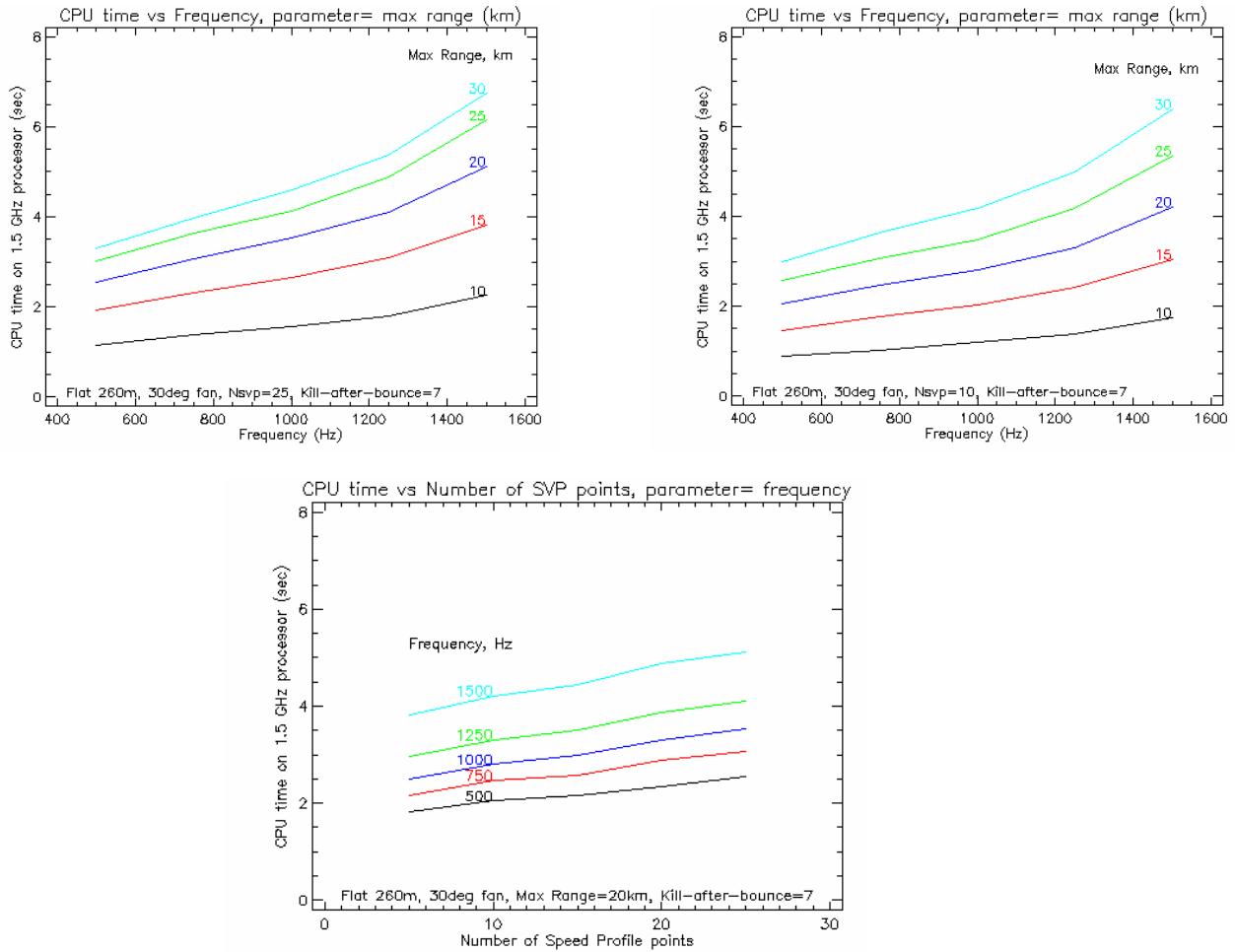
Figure 16. CPU time vs frequency and number of profile points for a 30ºangle fan allowing only 7 bounces. Upper left uses a 25 point SSP, upper right uses a 10 point SSP. Lower graph uses a max range of 20km.

2.5.1.1 *Summary of other timing factors comparisons*

The choice of a 30º fan and a kill-after-bounce number of 7 would produce less than 2 dB error on average at 1000 Hz over the range and depth of the computation, (and less than 1 dB beyond 2km) as compared to a higher-accuracy solution that takes twice as long to run. Given that the bottom loss is certainly unknown to within 1 dB, I feel that this computationally-induced error is entirely acceptable. Particularly since, for this application of LRT tracking, the tracker's logic assumes an uncertainty in signal excess of 10dB (small) to 60dB (large). [See, Stone and Osborn, "Effect of environmental prediction uncertainty on target detection and tracking", SPIE, 2004, section on simulation results]

3.   Task 2 - Simulated active products and usage

The second task in this study was a simulation of the steps required to construct the input tables for the LRT tracking algorithm. Using the information obtained from Dr. Larry Riddle [email], I configured Bellhop-DRDC to construct arrival tables and from these SALT tables, I saved arrays of TL as a function of asset identifier (source, towed array or one of 16 buoys), range, depth and bearing: TL(asset, bearing, r, z). Dr. Riddle specified using the peak arrival at each [r,z] coordinate, rather than the total as he felt this might better simulate a very short pulse.

The Bellhop-DRDC_SE settings for these tests were a frequency of 1000 Hz, an angle fan of 30º (±15º), a kill-after-bounce number of 7, a maximum range of 20 km, a range spacing of 0.5 km, and 51 receiver depths. The reverberation was summed for the surface and bottom and stored as RL(asset, bearing, r), where the arrival time of the reverberation is converted to a range by r = t *1500. Details of the reverberation calculations for a bistatic geometry are discussed in the annex. Normally RL would have been integrated over bearing and would be presented as a function of time, however Dr. Riddle specified this form. Actually it would not affect the runtime materially to sum over bearing rather than store by bearing. The beam patterns were not included in the calculations, but if they are read from a table, the computation will not add any extra runtime since the angles needed to index the beam patterns are available in the SALT tables.

The sequence of operations used for these tests is
1. Start CPU timer
2. Generate SALT tables for assets by:
   a. Loop over asset id
   b. Loop over bearing
   c. Copy the environment specific to that asset and bearing into input arrays
   d. Call Bellhop-DRDC_SE - Generate arrival tables
   e. Loop over range and depth
   f. Locate the index of the peak arrival at [r,z] from the arrival tables
   g. Transfer table entry of peak energy to asset storage arrays, TL(asset, bearing, r, z) applying beam pattern using launch angle from table.
   h. At z = surface and bottom, transfer four SALT entries (energy, launch angle, scattering angle and time) to surface and bottom reverberation storage arrays, SRL(asset, bearing, r, 4) and BRL(asset, bearing, r, 4)
   i. End all loops
3. Compute Reverberation for receiver assets using stored tables by:
   a. Loop over asset ids 2 to 18 (asset 1 being the source)
   b. Loop over bearing
   c. Loop over range, set time = range/1500.
   d. Call BottomReverb(asset, bearing, time) – using Ellis&Franklin Scattering Strength
   e. Call SurfaceReverb(asset, bearing, time) – using Ogden&Erskine Scattering Strength
   f. Sum the two reverberations and store in an array RL(asset, bearing, r)

g.   End all loops
4.   End CPU timer

The first test results are shown in Figure 17. This sequence was designed to represent a full setup of a source and 17 receiving assets that would be required before the start of the exercise. That is, in the step 2a of the sequence, the asset loop runs from 1 to 18. The time for this full setup is of the order of 10 minutes depending on the number of bearings needed.
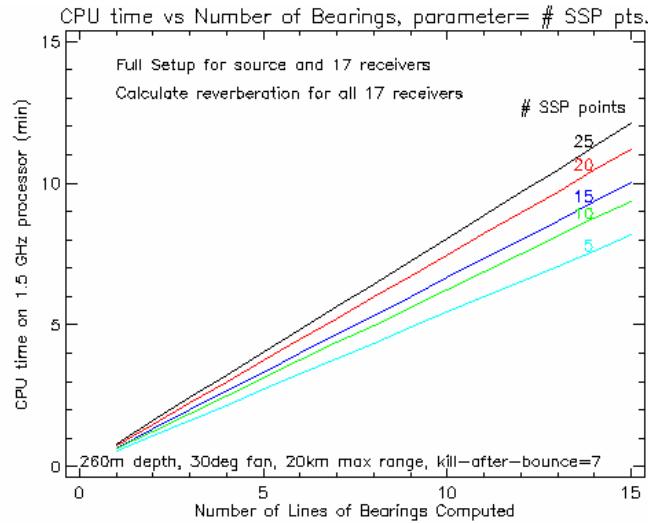
Figure 17. Full Setup time in minutes as a function of the number of lines of bearing and number of SSP points.

The second test results are shown in Figure 18. This sequence was designed to represent an update of the acoustic fields and reverberations that would be executed on a ping-by-ping basis. For this update, I assumed only the source and towed array would be changing position, and therefore in the sequence step 2a, the number of assets needing an updated set of SALT tables would be 2. The reverberation asset step 3a would still go from 2 to 18 since the changed position of the source means the reverberations to all other receivers will have changed, but the algorithm will use the existing receiver SALT tables that were generated from the setup run before the test began.

Figure 18 shows update times of the order of one minute using a 1.5GHz Pentium 4 processor to update TL for source and towed array and RL for all assets. Other potential update time issues might be the time required to retrieve and update the bathymetry track of the moving assets and the time required for the LRT algorithm to perform.
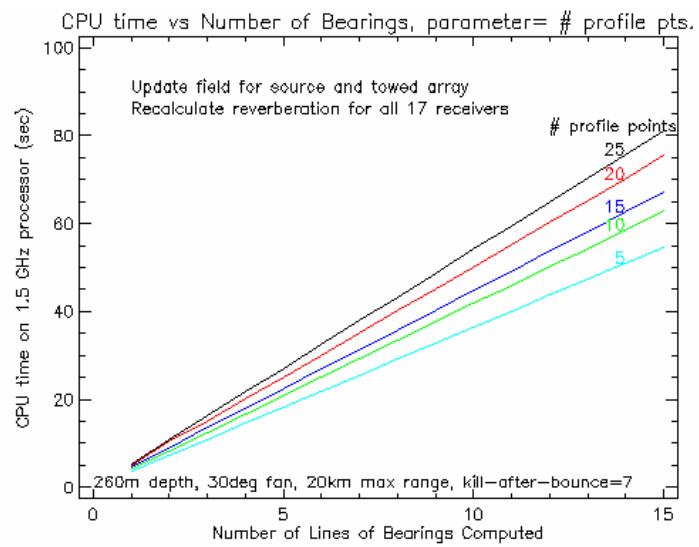
Figure 18. Update time in seconds as a function of the number of lines of bearing and number of SSP points.

4.   Summary

This research is designed to provide support for active sonar projects resulting from the bilateral agreement that has recently been signed with the US Navy to jointly investigate tactical oceanography technologies. In the context of the tracking exercise requirements, the model Bellhop-DRDC has been enhanced to produce active transmission loss and reverberation. Critical to the implementation of this model in the tracking exercise is the runtime. This report documents the parameters that affect runtime in Bellhop and recommends a configuration designed to provide the best result for the LRT tracking exercise in terms of the accuracy/runtime trade-off.

Specifically, a Scotian shelf area was chosen as a representative exercise environment. This environment features a downward refracting sound speed profile that causes all propagation to have numerous bottom interactions. Based on the timing and accuracy tests described in this report, it is recommended that for operation at 1000 Hz or higher in 260m water depth or less, the angle fan can be set to 30° (±15°) and a kill-after-bounce number of 7 can be safely employed to show less than 2dB error over all range and depth points in a 20km box.

Using this configuration in Bellhop-DRDC_SE, a simulated test sequence was constructed to compute arrays of transmission loss and reverberation for 18 assets (one source, one towed array and 16 buoys) as a function of bearing angle, range (1/2 km spacing out to 20km) and depth (51 points in 260m depth). This sequence was exercised for various numbers of lines of bearing and SSP points. These tests showed that the runtime needed for an initial calculation for all 18 assets ranged up to 12 minutes for 15 lines of bearing. The ping-by-ping update runtimes ranged up to 80 seconds for 15 lines of bearings and the 2 moving assets (one source and one towed array). These times were recorded using a 1.5GHz Pentium 4 processor.

If these run times are still too long, especially when added to additional potential update time issues such as the time required to retrieve and update the bathymetry track of the moving assets and the time required for the LRT algorithm to perform, then there is one more option available. That would be to take advantage of the shallow source and receivers' depths in bottom-bounce dominated propagation conditions and make an approximation to the incoherent acoustic field by using an asymmetric angle fan from 0 to +15°, and multiplying the resulting field by two. This approximation assumes the upward launched rays would closely follow the downward launched rays, having little surface loss and little range translation. It also assumes there is no direct path. Finally it assumes the short-range phenomenon of Lloyd's Mirror is not important. This approximation should cut the runtime of the sequence almost in half, however I can only recommend it as a last resort and its accuracy would have to be tested using the actual sound speed profile and bathymetry at the exercise site to ensure its acceptability.

Annex - Bistatic Reverberation Calculations

The geometry for a bistatic reverberation is shown below. S represents the source position and B represents the buoy position. The reverberation SALT tables obtained from the first step of the sequence in Section 3 contain the energy, launch angle, scattering angle and time stored as a function of asset id, bearing, and range. The bearing angle φ_b from the buoy, the separation in time of the source and buoy f, and the total travel time t are given at the start of the computation.

We need to solve for t_b, t_s, and φ_s in order to find the indices in the reverberation SALT tables for this geometry.
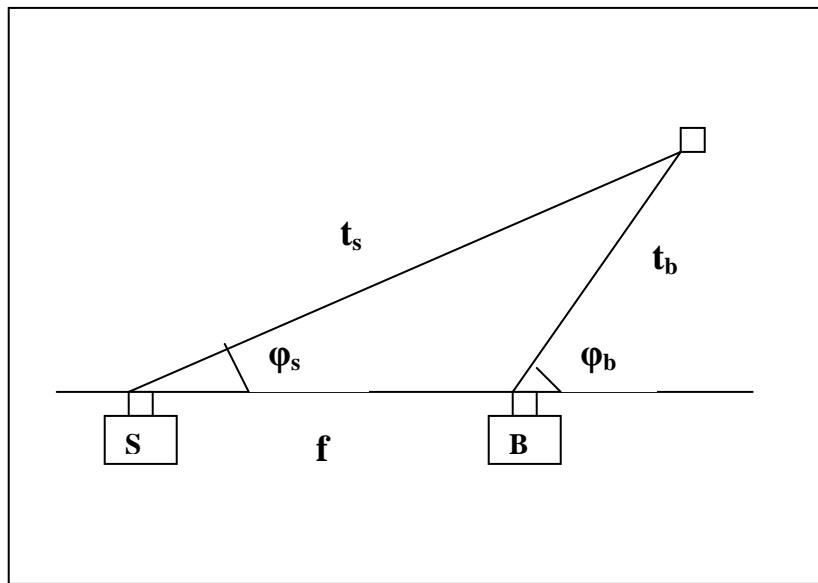
For the above triangle,

the law of sines is $t_s / \sin(\pi - \varphi_b) = t_b / \sin(\varphi_b)$,

the law of cosines is $t_s^2 = f^2 + t_b^2 - 2ft_b \cos(\pi - \varphi_b)$,

and for an ellipse of equal travel times, $t = t_s + t_b$

and the scattering area is $dA = t_b \, dt \, d\varphi$.

Substitute $t_s = t\text{-}t_b$ into the law of cosines and solve for t_b.

$$t_b = \frac{t^2 - f^2}{2} \frac{1}{t - f \cos(\pi - \varphi_b)},$$

Then, solve for t_s, from $t_s = t\text{-}t_b$,

Finally solve for the source bearing angle from the law of sines $\sin \varphi_s = \sin(\pi - \varphi_b)(t_b / t_s)$.

Locate in the source and buoy Reverberation SALT tables the index of entries at these bearings and times and extract the bottom scattering angles θ, the launch angles θ_i and the acoustic energies E. The launch angles can be used to impose a beam pattern on the energies as desired from a beam pattern table. Then the reverberation is assembled as the product of the energies, scattering strength and area.

$$R(\varphi_b, t) = E_s E_b \ S(\theta_s, \theta_b) \ dA$$

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